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Task 1

Summary Report

August 1977

Infrared Imagery of Shuttle (IRIS)

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Task 1

INFRARED IMAGERY OF SHUTTLE (IRIS)

Approved

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SUMMARY

The feasibility of remote, high-resolution infrared imagery of the Shuttle Orbiter lower surface during entry to obtain accurate measurements of aerodynamic heat transfer has been demonstrated. Using available technology, such images can be taken from an existing aircraft/telescope system (the C141 AIRO) with minimum modification or addition of systems. These images will have a spatial resolution of 1 m or better and a temperature resolution of 2.5% between temperatures of 800 and 1900 K. Data reconstruction techniques will provide a geometrically and radiometrically corrected array on addressable magnetic tape ready for display by NASA.

Schedule considerations dictate a timely start in FY1978 to mesh with the first Shuttle Orbiter test flights in late 1979 and early 1980. Additional work in the form of subsystem breadboards is recommended to prove principle before system construction.

CONTENTS

INTRODUCTION

Early in 1976 NASA-Ames Research Center expressed an interest in the Infrared Imagery of heated surfaces such as the Shuttle Orbiter during reentry. Necessary information to substantially reduce the weight and cost of thermal protection systems of future space transportation systems could result from accurate flight data on: (1) the lower surface heating rate distribution, (2) the location of boundary-layer transition, and (3) location and extent of flow separation in front of control surfaces. This imaging would be obtained by an appropriate telescopic sensor system mounted in one or more chase aircraft stationed appropriately along the Shuttle reentry ground track.

Initially, an approach was taken to fly the chase aircraft perpendicular to the Shuttle flight direction to maximize the viewing time (cross track approach). It became apparent that within the maximum viewing time (10 to 20 sec), no significant surface temperature changes would occur precluding the desire for multiple images. In addition, the angular rates between the Shuttle and chase aircraft became complex and were excessive, requiring major redesign of any telescope stabilization system.

At this point, NASA-Ames Research Center undertook an in-house study and generated an approach where the chase aircraft flew parallel to the Shuttle ground track (along-track approach). Since multiple images or integration times in excess of a few microseconds were unnecessary, the streak camera idea was introduced. The streak camera, as it applies here, is a linear array of detectors at the image plane of a telescope. The detectors are sampled at a rate compatible with image motion to obtain a desired resolution. Tracking of the object is unnecessary as long as the object passes through the field-of-view of the telescope. One image is obtained for each linear array of detectors.

The feasibility study contract was then awarded. NASA directed the contractor to undertake the study based on the in-house findings. These tasks included:

1) An IR technology survey to investigate the current state of sensor technology;

2) A preliminary design of all subsystems with regard to environment, power, and support requirements;

3) A system performance describing the end-to-end capabilities of the design including error sources; and

4) A cost and schedule assessment for the design, fabrication, assembly, installation, and support during the first six Shuttle development flights. The purpose of this report is to summarize the results of the above analysis.

EXPERIMENT OBJECTIVE

The objective of the experiment is to obtain high resolution (1 m or better) surface maps of the Shuttle Orbiter lower and side surfaces with a temperature accuracy of at least 2.5% during the peak heating, flap deflection, and transitional heating periods of the reentry profile. This information is required to verify computational predictions and experimental extrapolations to provide data for possible TPS block changes.

Predicted temperature distribution and transition points for the Shuttle Orbiter reentry profile 14414 have been established (Ref Fig. 1). All six orbital flight test (OFT) reentry profiles are expected to have similar temperature distributions; however, the time from entry when these events occur will be different. Maximum temperatures on the windward and side surfaces are not expected to exceed 1900 K and are generally above 600 K during the time periods of interest.

Implications associated with the experiment cover many facets. First are the variations in Shuttle Orbiter altitude, velocity, angle-of-attack, and bank angle which must be accommodated. The key points of interest during the reentry (peak heating, flap deflection, and transitional heating) correspond to a given time from entry for a given reentry profile. OFT 1, 2 and 3 reentry profiles are slightly different from profile 14414. As an example, peak heating occurs at T = 400 sec for orbit reentry 14414 and at T = 282 sec for OFT 1. This corresponds to a Shuttle Orbiter altitude of 74.3 km, a velocity of 7.16 km sec, an angle-of-attack of 40°, and a bank angle of 74°. To obtain accurate high resolution data with one system for these varying conditions requires a versatile observing platform and data system.

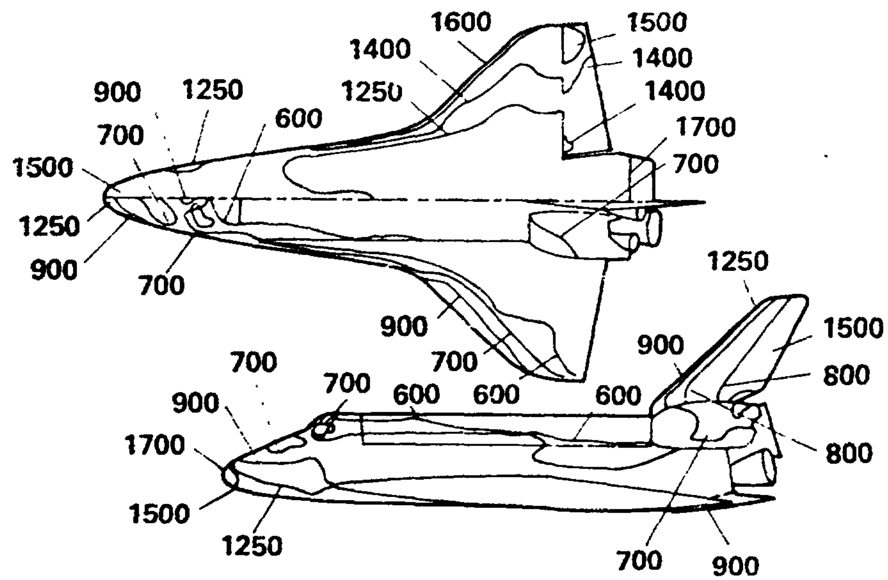
A second consideration is associated with the expected radiation from the Shuttle Orbiter. At temperatures ranging from 600 to 1900 K, a black body will have its radiation peak between 1.5 and 4.8 micrometers. For these temperatures, the wavelengths for which the first derivative of radiant energy with temperature is a maximum occur between approximately 1.3 and 2.7 micrometers. This suggests that the optimum detector/filter response should be about 2 micrometers with a limited spectral bandwidth.

Thirdly, the requirement for at least 1 m resolution at a maximum range of 75 km implies an angular resolution of 1.7 arcsec with foreshortening from the nonnormal aspect of the surface to the line-of-sight of 40° maximum. At a wavelength of 2.0 micrometers, a diffraction limited telescope would require an aperture of at least 30 cm. An aperture of 60 to 100 cm is

SHUTTLE ORBITER MAXIMUM TEMPERATURE CONTOURS

FIG. I

Reentry Profile
14414



NOTE: ALL TEMPERATURES IN °K

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suggested by considering other degrading factors such as atmospheric effects, finite detector elements, image motion, and the unavailability of a perfect diffraction limited telescope.

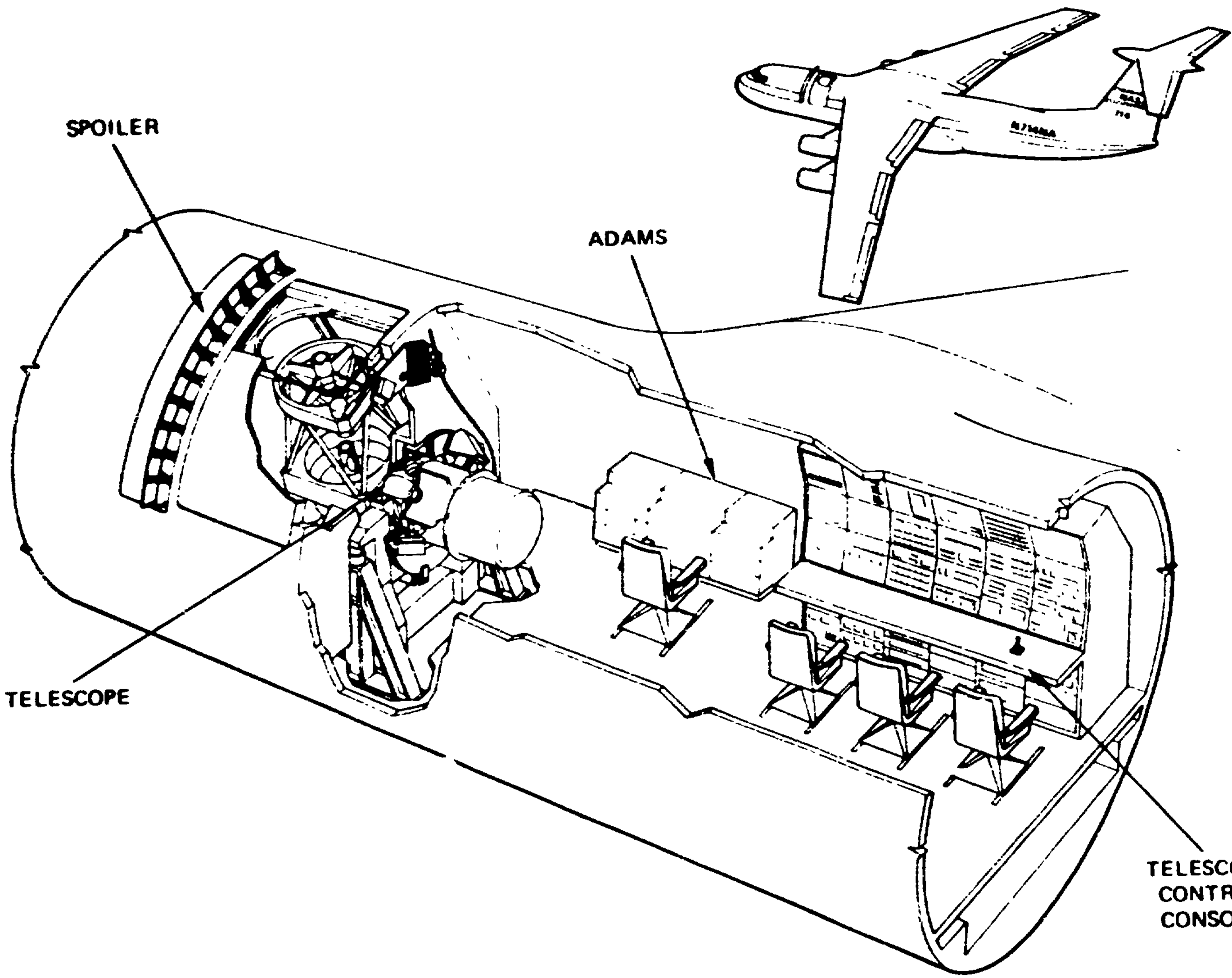
In addition to the desirability of observing each OFT at a unique position along the reentry path, a verification of system performance before OFT 1 is necessary. A test flight using an aircraft that can simulate expected angular rates, temperatures, and angular size will provide the verification. The only candidate aircraft found that approaches these requirements is the YF-12 flying at an altitude of 24.4 km at 1.03 km/sec.

Finally, the aircraft should be capable of a cruising altitude of 14 km (above most atmospheric water). This is arrived at by considering the wavelength requirements for maximum sensitivity to the expected temperature range of 1.5 to 2.5 micrometers. The versatility required of the observing platform is to ensure proper position with respect to the Shuttle Orbiter for a variety of reentry conditions. In addition, this aircraft must have the capacity for a telescope with an aperture of 60 to 100 cm.

Several existing airborne platforms and a ground station were considered during the course of this study. The platform that best accommodates the requirements for this experiment is the C-141 airborne infrared observatory (AIRO) based at NASA Ames Research Center. The NASA C-141 AIRO meets all the requirements of locatability and altitude; the 91.5-cm telescope on board will provide a Shuttle surface resolution of 1 m or better (Fig. 2). In most high temperature areas, the resolution will approach 0.7 m for the longest range condition (peak heating) and approach 0.5 m for shorter range conditions. In addition, the telescope elevation is adjustable between +35 and +75° above waterline and can be optimized for each Shuttle Orbiter reentry condition. The on-board stabilization and telescope drive system is adequate. No modifications are required other than gain adjustments on some servoloops. This aircraft is the only candidate with an on-board system control and data handling computer (HP2100). The streak camera technique is directly adaptable to the telescope similar to current IR experiments. The only modification required is to mount an acquisition system on the telescope headring. It will not interfere with any operation of the telescope and does not have to be removed for other experiments. The aircraft and telescope facilities are best suited for this experiment.

All further discussions for this experiment will be directed toward use of the NASA C-141 AIRO. Each of the system augmentations required for Shuttle infrared imagery experiment will be summarized in the following sections.

FIG. 2



NASA C141 Airborne Observatory

The three major subsystems identified (Acquisition System, Image Plane System, and Data Handling System) were evaluated for the design requirements for each. In addition, an overall performance of the whole system was performed and an approach to data reconstruction identified. Finally, a cost breakdown for design, build, test, and installation of the system, including flight support, is given.

ACQUISITION SYSTEM

The design requirements of the Acquisition System are:

1) To find the Shuttle while accounting for its uncertainty in position with respect to the aircraft,

2) To lock-on the Shuttle and track it thereby providing an elevation error to the main telescope drive system, and

3) To maintain this lock until the Shuttle image passes within ±2.5 arcmin of the telescope line-of-sight. This can be accomplished by mounting the acquisition system on the main telescope with the gimbal axis 90° to both the telescope elevation axis and line-of-sight. As the telescope is driven in elevation based on the error signal received from the acquisition system, both move in elevation reducing the error signal.

The uncertainty of the Shuttle position with respect to aircraft position and the maximum range of elevation adjustment dictates the field-of-view (FOV) of the acquisition system to be 9°. The cross track error of the Shuttle can be 15 km and the altitude error can be 3 km when the acquisition range is at least 90 km. The along track error of the Shuttle is of no concern when flying parallel to the Shuttle.

The design chosen for the acquisition system is an infrared refracting lens that provides an image of the 9° field on a rotating reticle (Fig. 3). Behind the reticle is a condensing lens and a cryostat-cooled indium-antimonide (InSb) detector. The whole system is mounted on a gimbal axis that is 90° to both the telescope elevation axis and the telescope line-of-sight.

ACQUISITION SYSTEM

FIG. 3

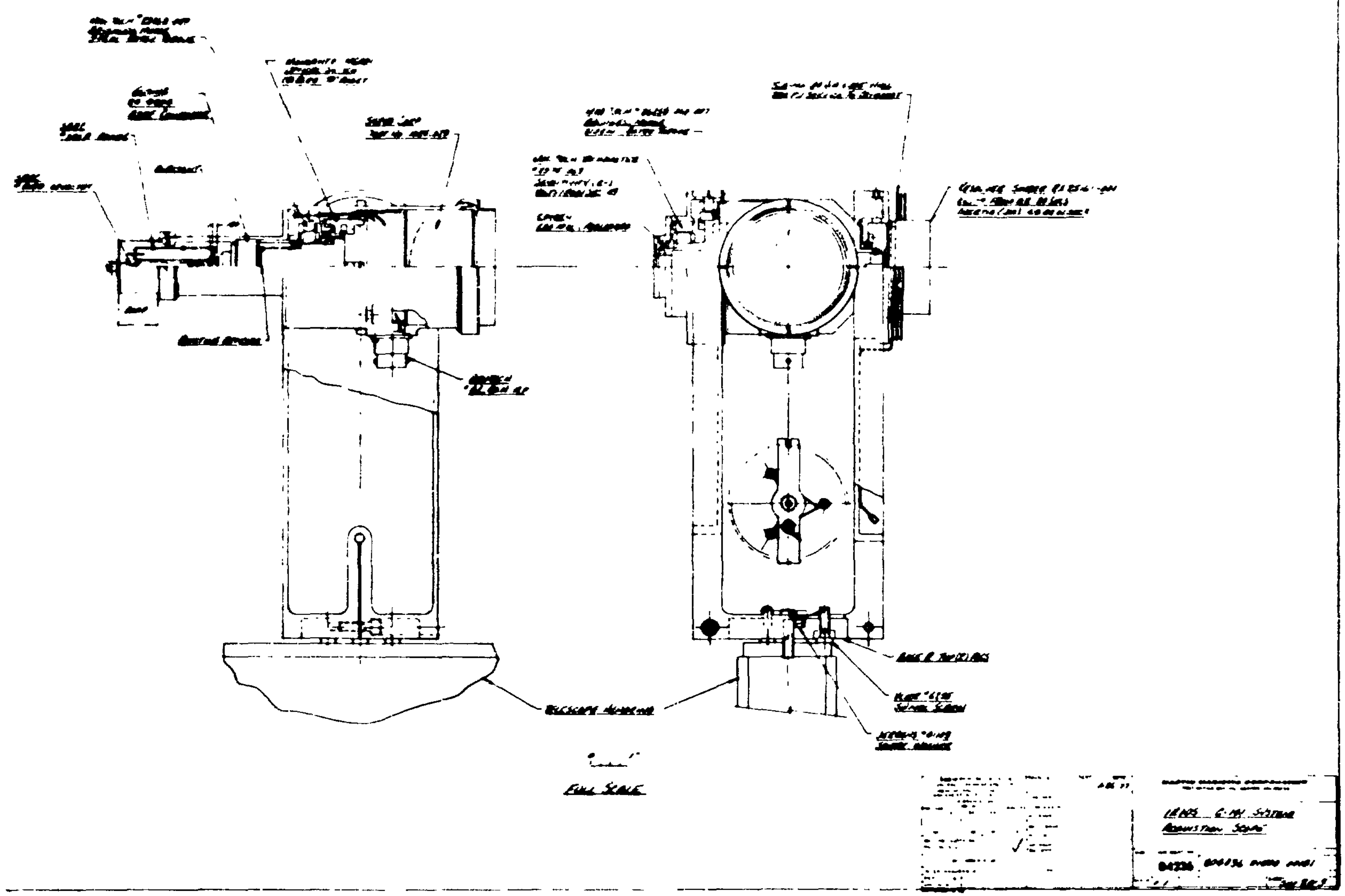


IMAGE PLANE SYSTEM

The design requirements for the Image Plane System are:

1) To maintain a state of readiness until the Shuttle image enters any detector field-of-view,

2) Be compatible with the 91.5 cm f/13.5 telescope image plane but autonomous in performance,

3) Provide redundancy, and

4) Finally provide adequate signal output to the data handling system under the worst-case encounter parameters with either the Shuttle or YF-12 calibration aircraft.

The streak camera approach to infrared imaging of the Space Shuttle imposes the following general requirements on the image plane detector array system:

1) The resolution elements (each detector) must be consistent with the target resolution requirements (e.g., 0.050 mm).

2) The image must be contiguous (no space) in the streak direction (Fig. 4);

3) The detector must respond to grey body radiation in the temperature range from 600 to 1900 K; and

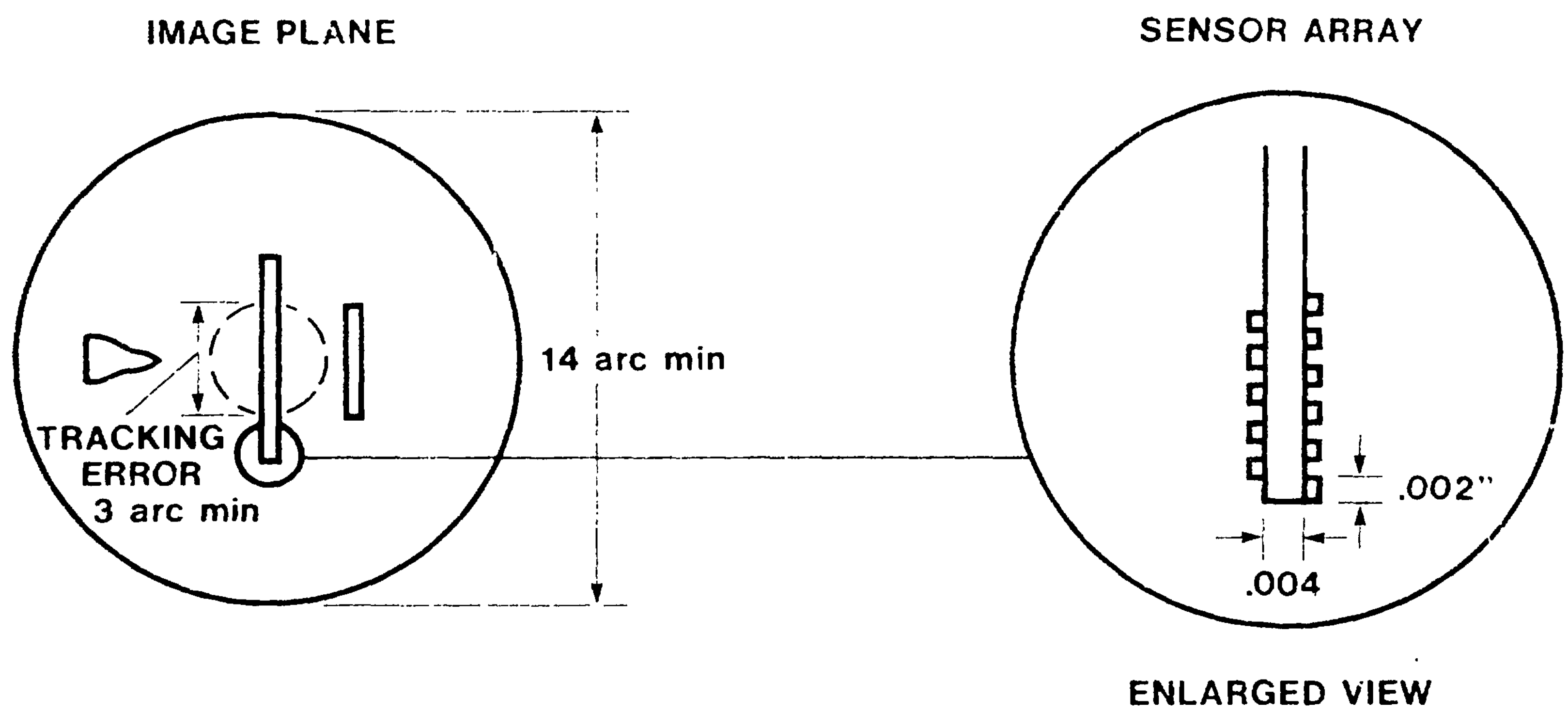
4) The detector-filter combination must be in a wavelength region such that the first derivative $\left(\frac{dW}{dT}\right)$ is large enough to yield the required Shuttle temperature resolution i.e., 5% (2½% design goal).

The Dewar assembly shown in Figure 5 is an approach to housing the detector array and amplifier assemblies to the main telescope while keeping the seal integrity of the airplane-to-telescope interface.

The detector array is located at the focal plane of the main telescope. The Dewar assembly is designed to cool the detector arrays and the bandpass optical filter. The detector leads will pass through the Dewar walls and then through hermetic seals to the amplifier boards located in the area around the Dewar. The amplifier board mounting system will allow easy access for trouble shooting and board-changing.

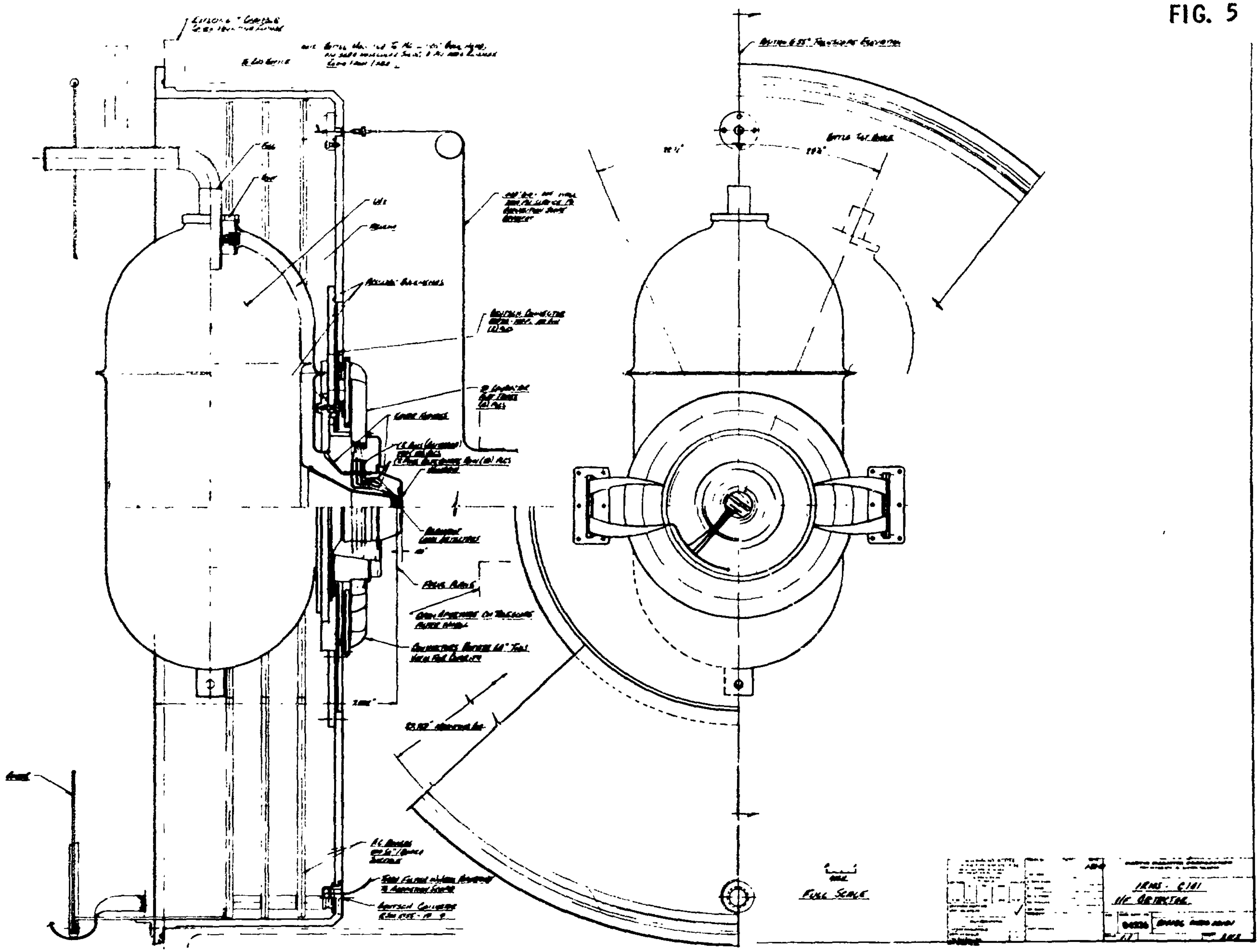
FIG. 4

PRIMARY TELESCOPE IMAGE PLANE



DEWAR ASSEMBLY

FIG. 5



DATA HANDLING SYSTEM

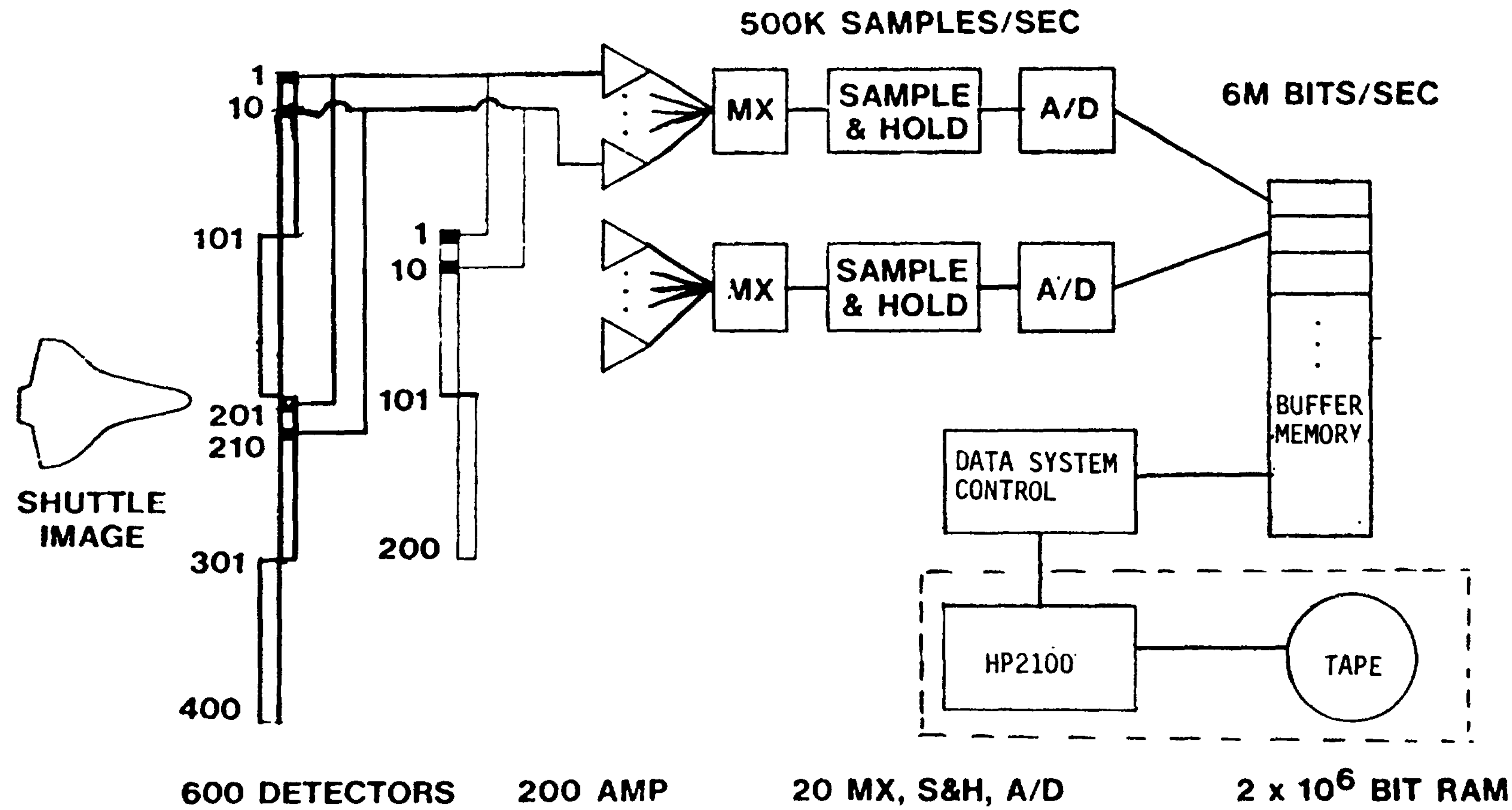
In its simplest form, the Data Handling System is required to interface the 600 indium antimonide detectors that form the two linear detector arrays (Fig. 6) in the focal plane of the C-141 main telescope and provide the C-141 ADAMS computer all the information produced during the passage of a single Shuttle image across the detector arrays. The design requirements come from two sources. The first set of requirements derive from the selection of a detector type, the associated array geometry, the image size dictated by the telescope optics, and the Shuttle flight path relative to the C-141. These elements are covered in other parts of this report but they drive design requirements in the data system. The second source of design requirements is the desired final form of the information gathered by this system. Those requirements involve parameters like measurement range and resolution.

Figure 7 shows the overall flow of information from the Space Shuttle to the C-141 telescope through the detectors and into the data system. These data are accumulated in the data system buffer and then read into the ADAMS computer and written onto computer tape. Figure 7 shows the system interfaces. It must be remembered that the ADAMS is an intrinsic part of the functional system. What is referred to in this report as a "data handling system" is only part of a system and will not function in a flight mode without the ADAMS.

Figure 6 is a more detailed data flow schematic and shows the paralleling of the 600 detectors into 200 analog measurement channels.

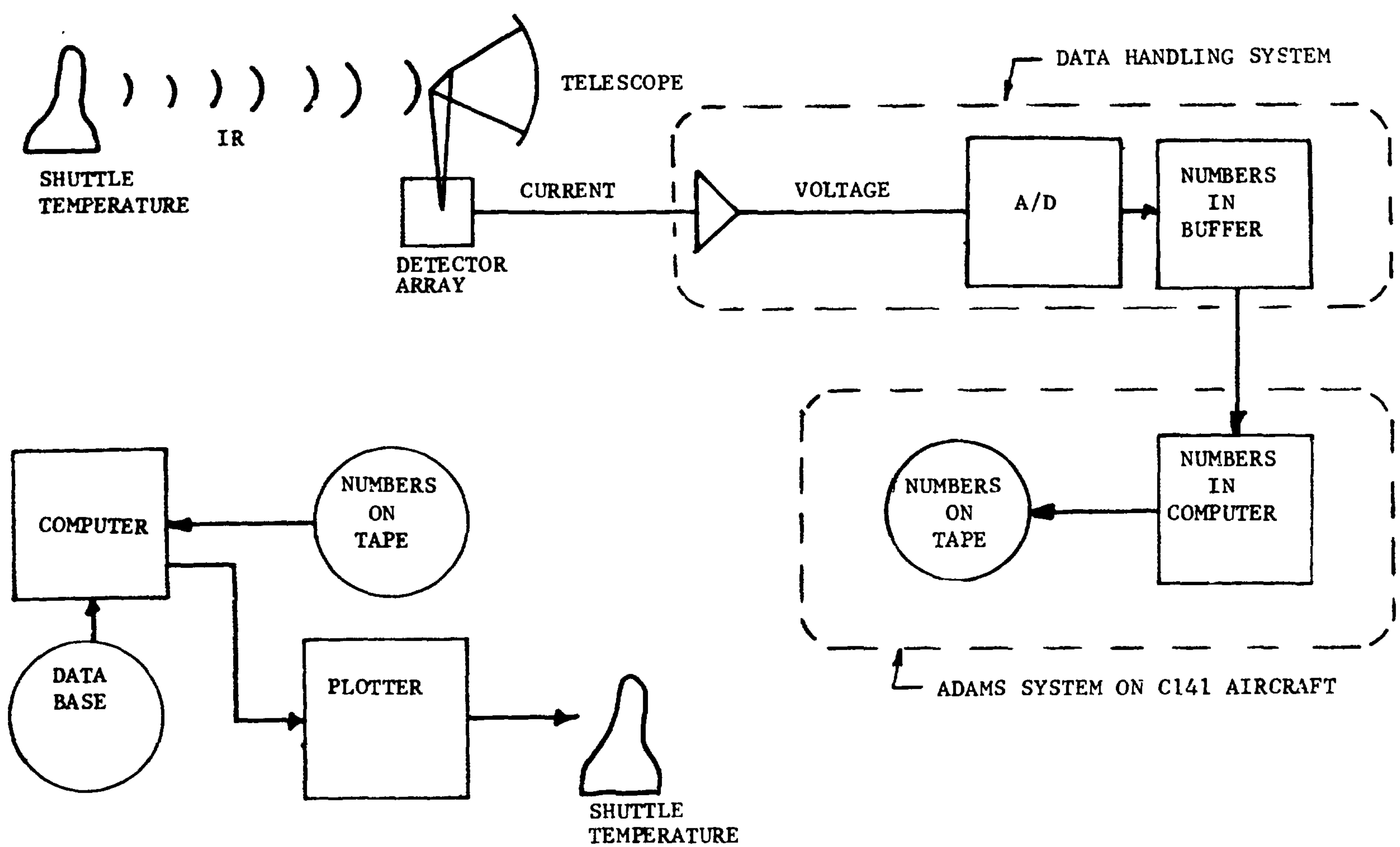
DATA HANDLING SCHEMATIC

FIG. 6



TEMPERATURE INFORMATION FLOW

FIG. 7



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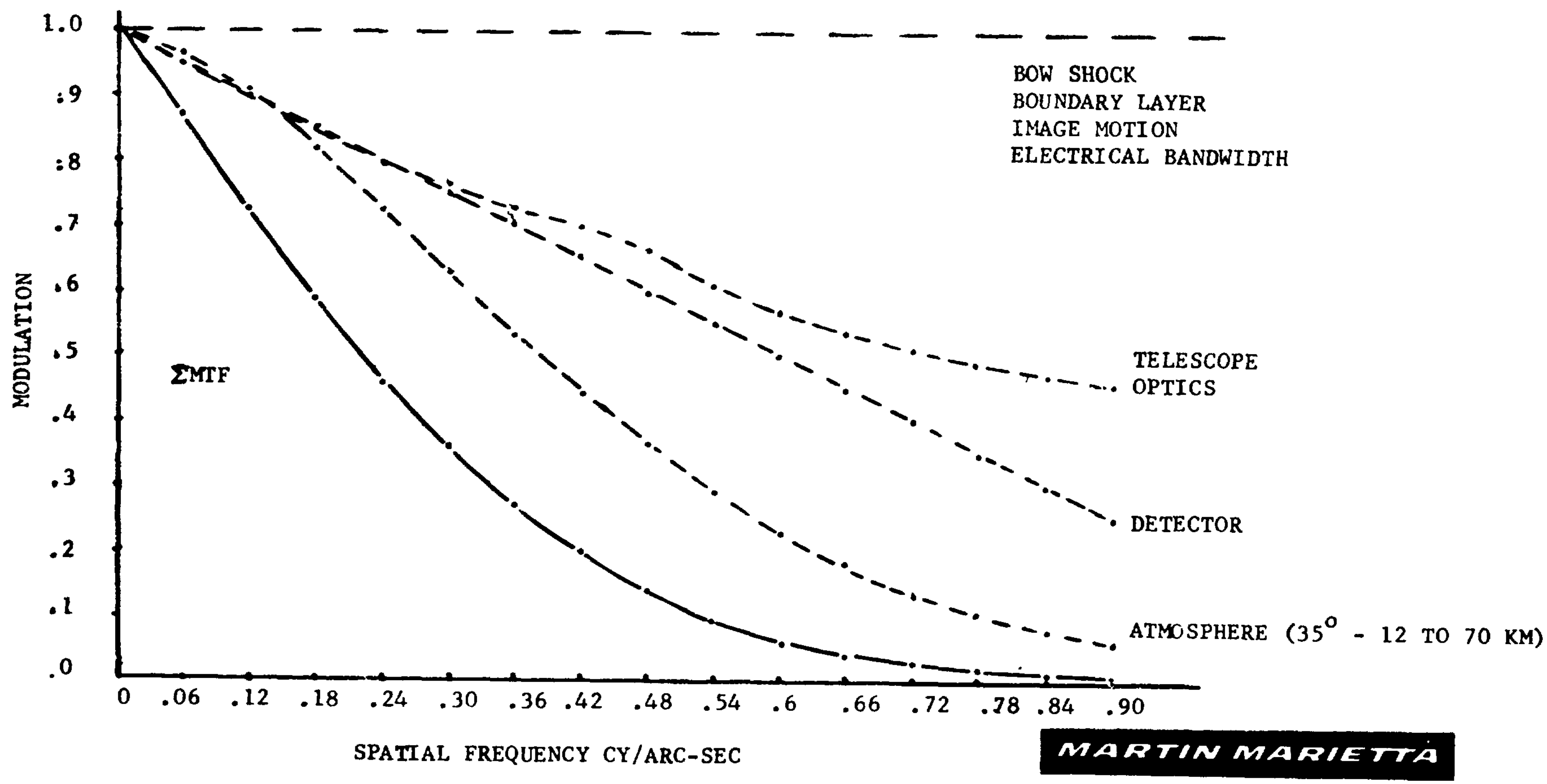
SYSTEM PERFORMANCE

The imaging system performance has been analyzed from the radiation source to the data storage point and includes the following effects; Shuttle flow field, atmospheric, aircraft flow field, telescope optics, image stabilization, detector, and background.

The summation of all effects governing the modulation transfer function (MTF) and ultimately spatial and temperature resolution is shown in Figures 8, 9 and 10.

ΣMTF

FIG. 8



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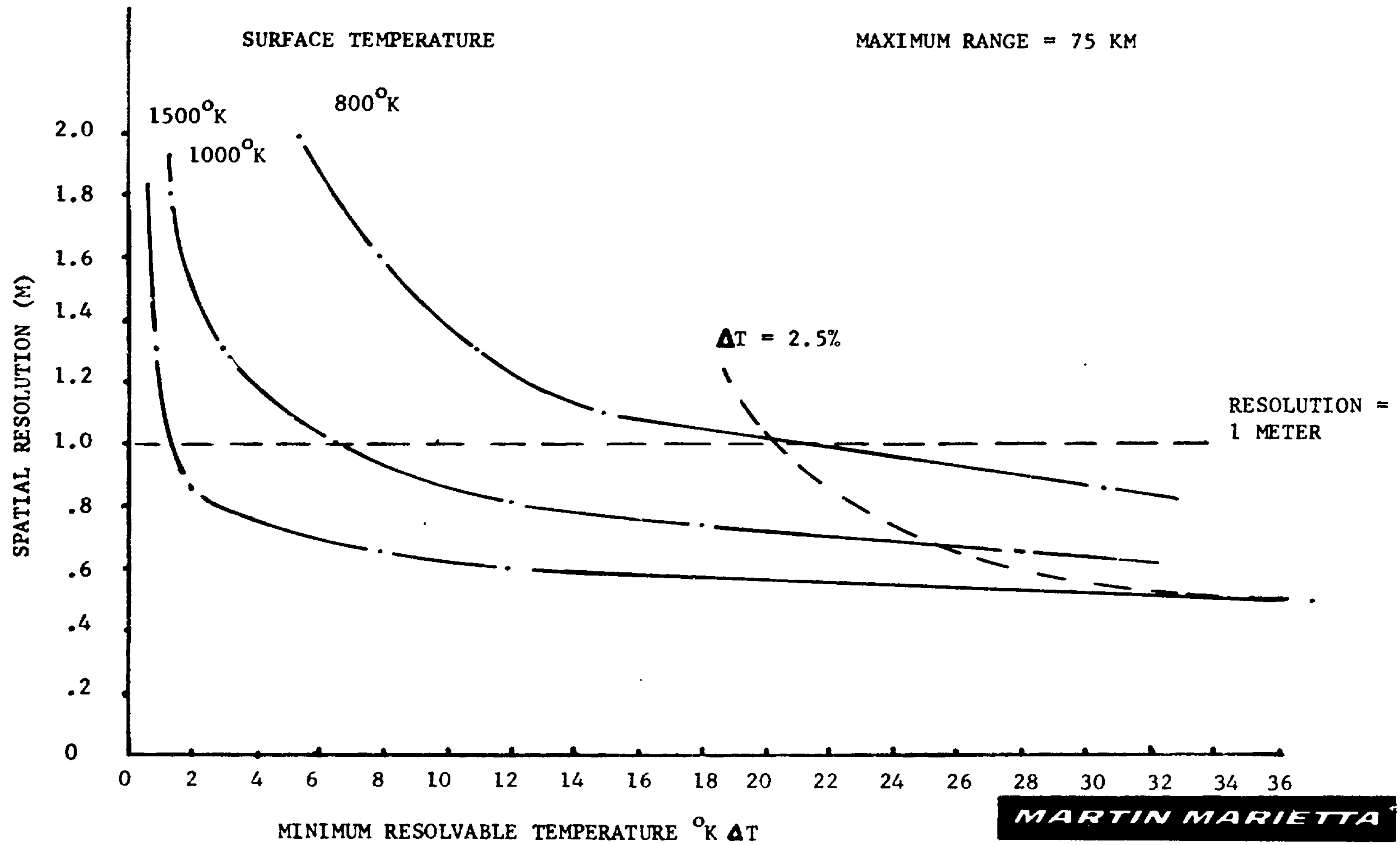
IMAGING SYSTEM PERFORMANCE (12 BIT DIGITAL CONVERSION) FIG. 9



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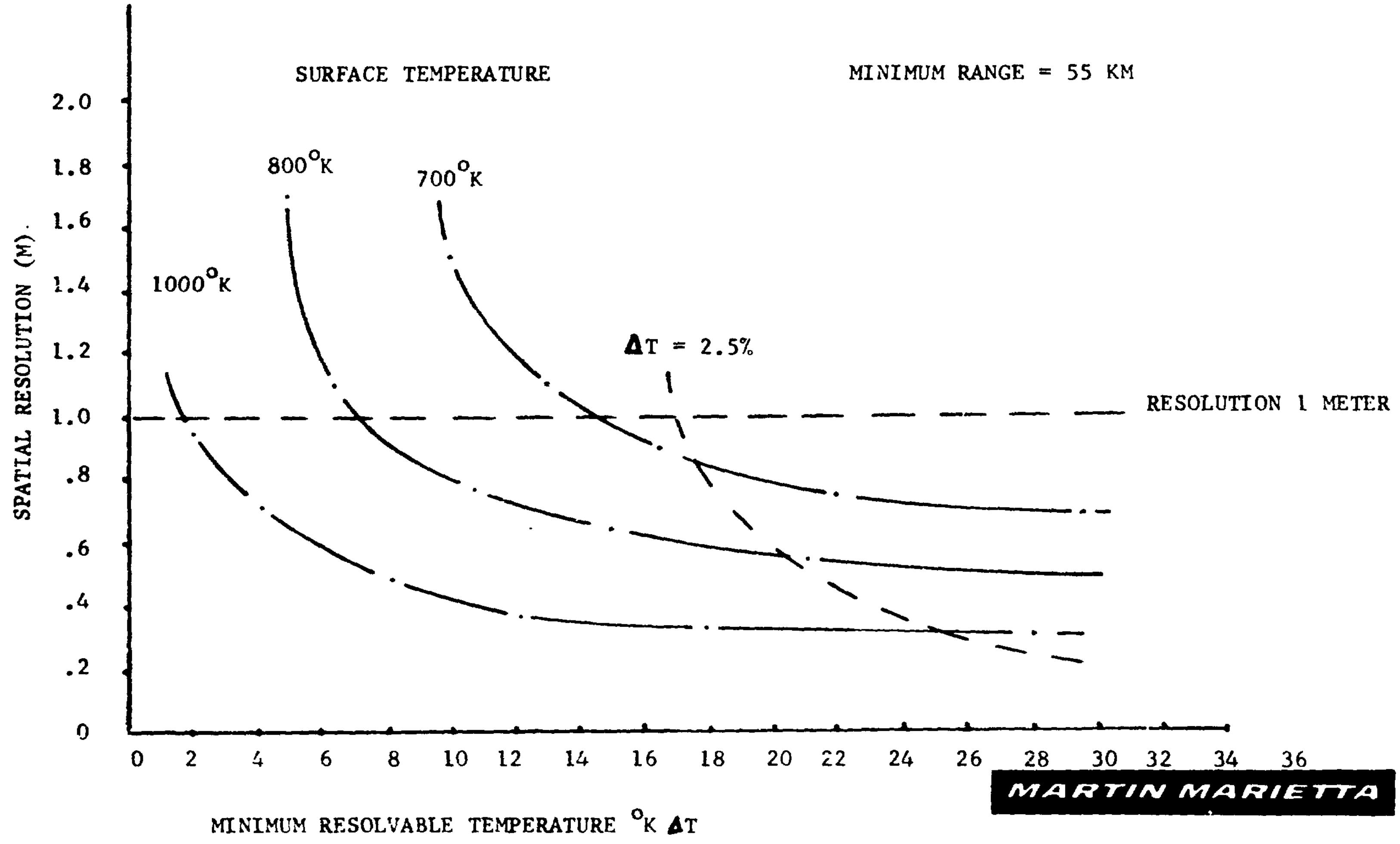
IMAGING SYSTEM PERFORMANCE (12 BIT DIGITAL CONVERSION) FIG. 10



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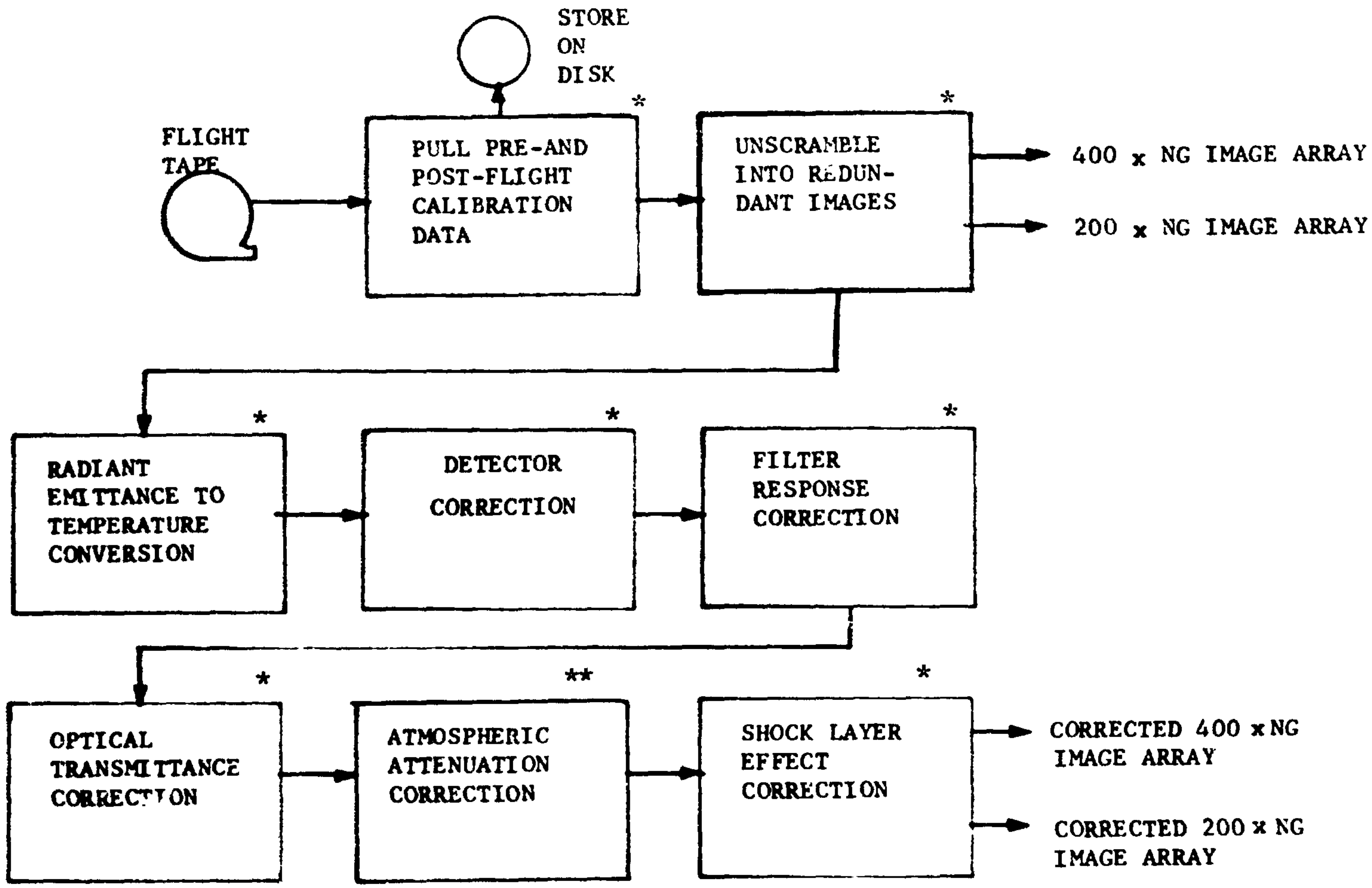
DATA RECONSTRUCTION

After the data have been acquired and recorded, there will be several levels of processing required to go from the flight tape to an output tape containing calibrated and corrected data suitable for further analysis by NASA Ames. This processing will consist of five major steps: (1) unscrambling, (2) intensity correction, (3) reconstruction, (4) geometric correction, and (5) calibration. Each of these steps is shown in Figure 11.

IMAGE PROCESSING/UNSCRAMBLE AND INTENSITY CORRECTION

FIG. 11



* NEW DEVELOPMENT
**EXISTING SOFTWARE

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COST

An estimate to perform the engineering, purchase parts including subcontracted items, fabricate, assemble test and install a complete system in the C-141 including flight support for six OFT flights is shown in Figure 12

PRELIMINARY PROGRAM COST BREAKDOWN

FIG. 12

	HOURS	PURCHASED PARTS	TRAVEL	COMPUTER
ENGINEERING DESIGN	7450		7K	
PROCUREMENT	1860	361.2K	6.3K	
ENGINEERING ASSEMBLY	2750		9K	
ENGINEERING TESTING	1800			
ENGINEERING SYSTEMS SUPPORT	2863		10K	
DENVER DATA SYSTEMS SUPPORT	2358		2K	7.5K
MFG/MODEL SHOP	1270			
QC SUPPORT	980			
PARTS ACCEPTANCE TESTS	450			
PROGRAM SUPPORT	2200			
	23981	361.2K	34.3K	7.5K

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RECOMMENDATIONS FOR FUTURE WORK

Two items have been identified in the feasibility study for possible investigation to establish operating tolerances. The first is the accuracy obtainable by the Reticle/Demodulation System as part of the Acquisition System. Error sources for tracking have been identified, but some assumptions as to Shuttle image size error and demodulation errors have been made. A breadboard of the subsystem would prove valuable in ascertaining tracking errors.

The second item is in the Data Handling System. The concept of tying three detectors to a common amplifier and then multiplexing 10 amplifiers to the sample and hold/A to D is sound but needs to be breadboarded to establish realizable data rates and amplifier noise. In addition, the dynamic range can be checked for available detector/amplifiers and an estimate made of minimum ΔT.

These two tasks are recommended for follow-on work to the feasibility study.

Figure 13 is an estimate of Engineering hours and purchased parts to complete these tasks and Figure 14 is a preliminary schedule for completion of the work.

FOLLOW-ON TASK ESTIMATE

FIG. 13

	HOURS	PURCHASE PARTS
TASK I - IMAGING SYSTEM		
BREADBOARD AMPLIFIER/DETECTOR SAMPLE & HOLD/AD	360	$12K
PERFORM DEVELOPMENT TESTS	290	
TASK 2 - ACQUISITION SYSTEM		
BUILD RETICLE/AMPLIFIER SYSTEM	240	$3.1K
PERFORM DEVELOPMENT TESTS	100	
SIMULATE SOFTWARE/SERVO ERRORS	220	$ .4K

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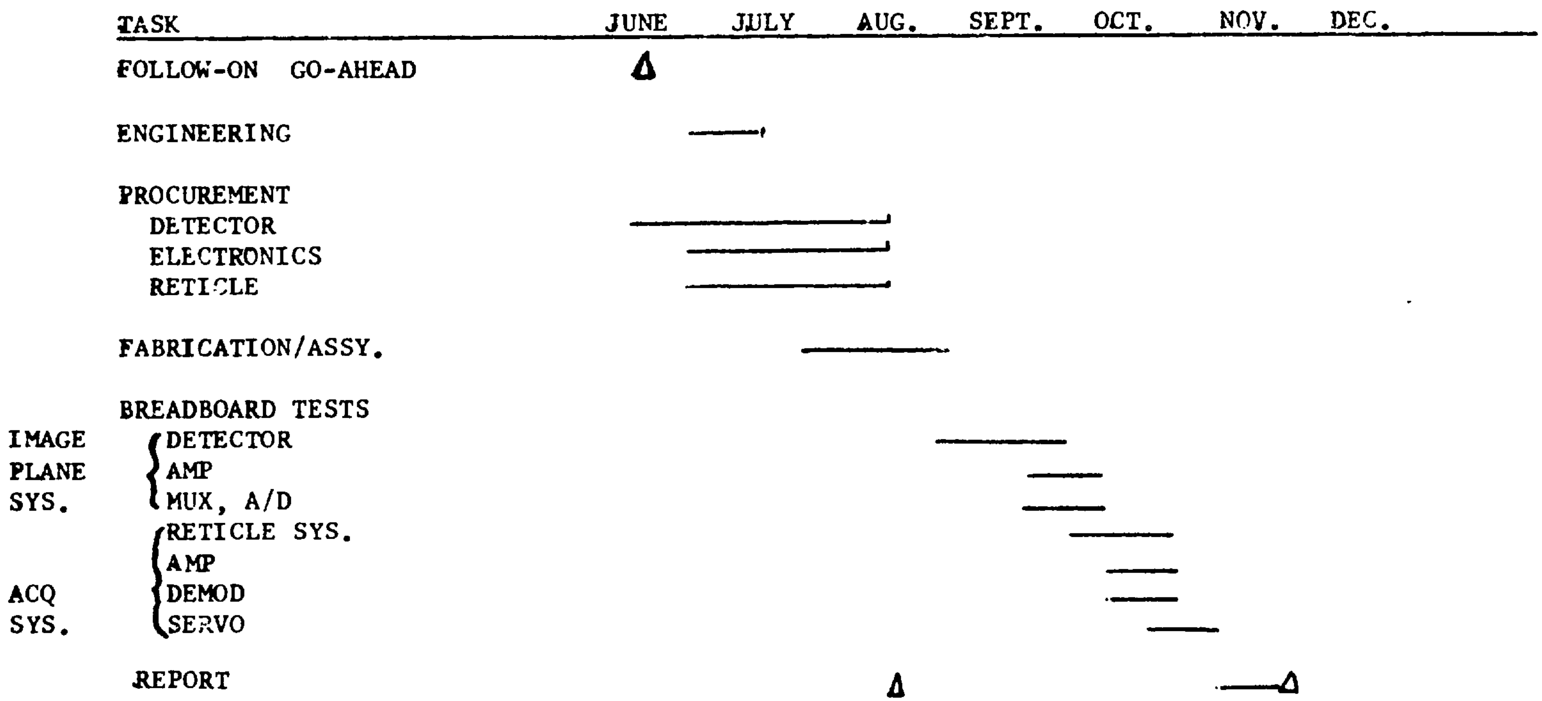
FIG. 14

INFRARED IMAGERY OF SHUTTLE - FOLLOW-ON CONTRACT SCHEDULE NAS2-9381



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CONCLUSIONS

The feasibility of remote, high-resolution infrared imagery of the Shuttle Orbiter lower surface during entry to obtain accurate measurements of aerodynamic heat transfer has been demonstrated. In summary, the experiment is both feasible, within the current technology level, and requires minimum modification to the existing NASA C-141 Airborne Infrared Observatory. The most important technical conclusions are as follows:

1) The four conditions of interest during the entry trajectory can be accommodated by an aircraft flying parallel to the Shuttle reentry ground track.

2) The temperature range that can be measured at an accuracy of 2.5% is from 600 to 1900 K depending on range. Temperatures below 700 K can be measured by relaxing the accuracy or rescaling the Data System to limit the upper temperature to less than 1700 K.

3) The spatial resolution obtainable for the worst-case encounter with the Shuttle Orbiter (i.e., greatest range and maximum angle between LOS and Shuttle lower surface normal) is 1 m at temperatures above 800 K. At higher temperatures and/or shorter ranges, this value can be as small as 0.4 m.

4) An Acquisition System using a 6.25-cm aperture telescope and a single indium-antimonide detector has been designed (preliminary) that will meet the acquisition requirements and will interface with the 91.5-cm telescope with minimum modification.

5) An Image Plane System using 600 indium-antimonide detectors in two arrays has been designed (preliminary) that requires no modification to the existing telescope.

6) A Data Handling System built of components available currently has been designed (preliminary) that interfaces with the experimentors station and HP2100 computer (ADAMS) similar to any infrared experiment data system.

7) Thermal information from the sides of the Shuttle Orbiter can be obtained with degraded performance (i.e., temperatures below 800 K) by flying the C-141 on the opposite side of the Shuttle ground track and in the direction opposite that which is optimum for lower surface viewing.